

# Cervical ossification of the posterior longitudinal ligament: factors affecting the effect of posterior decompression

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**Objective:** Decompression procedures for cervical myelopathy of ossification of the posterior longitudinal ligament (OPLL) are anterior decompression with fusion, laminoplasty, and posterior decompression with fusion. Preoperative and postoperative stress analyses were performed for compression from hill-shaped cervical OPLL using 3-dimensional finite element method (FEM) spinal cord models.

**Methods:** Three FEM models of vertebral arch, OPLL, and spinal cord were used to develop preoperative compression models of the spinal cord to which 10%, 20%, and 30% compression was applied; a posterior compression with fusion model of the posteriorly shifted vertebral arch; an advanced kyphosis model following posterior decompression with the spinal cord stretched in the kyphotic direction; and a combined model of advanced kyphosis following posterior decompression and intervertebral mobility. The combined model had discontinuity in the middle of OPLL, assuming the presence of residual intervertebral mobility at the level of maximum cord compression, and the spinal cord was mobile according to flexion of vertebral bodies by 5°, 10°, and 15°.

**Results:** In the preoperative compression model, intraspinal stress increased as compression increased. In the posterior decompression with fusion model, intraspinal stress decreased, but partially persisted under 30% compression. In the advanced kyphosis model, intraspinal stress increased again. As anterior compression was higher, the stress increased more. In the advanced kyphosis + intervertebral mobility model, intraspinal stress increased more than in the only advanced kyphosis model following decompression. Intraspinal stress increased more as intervertebral mobility increased.

**Conclusion:** In high residual compression or instability after posterior decompression, anterior decompression with fusion or posterior decompression with instrumented fusion should be considered.

**Keywords:** Finite element method, Cervical ossification of the posterior longitudinal ligament, Posterior decompression, K-line; instrumented fusion

## Introduction

Cervical ossification of the posterior longitudinal ligament (C-OPLL) is a disease causing cervical myelopathy through ossification of the posterior longitudinal ligament (OPLL).<sup>1</sup> The surgical procedures applied to this disease are broadly divided into anterior decompression with fusion and posterior decompression, which is typified by laminoplasty.<sup>1,2</sup> Anterior decompression with fusion is technically difficult and is also reported to cause complications, especially when multiple vertebrae

are operated. However, because it technically facilitates laminoplasty and also achieves favorable outcomes in many cases, the procedure is often selected.<sup>3-6</sup> Meanwhile, in cases of high residual anterior compression or a mobile spinal cord at the high level of cord compression, laminoplasty alone is not adequate to control postoperative kyphotic changes. There are also reports that better outcomes are achieved by anterior decompression with fusion or posterior decompression combined with instrumented fusion.<sup>2,3,7,8</sup>

We developed 3-dimensional finite element method (3D-FEM) spinal cord models of hill-shaped OPLL, whose prognosis is considered to be poor,<sup>8</sup> and reported

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that static and dynamic compression is associated with the occurrence of cervical myelopathy due to C-OPLL.<sup>9</sup> However, stress analysis had not been performed in a condition where decompression was performed. In the present study using the same models, the effects of posterior decompression for C-OPLL, as well as the effects of the presence of residual compression and instability on the cervical spinal cord, were evaluated. The results are reported here.

## Material and methods

The ABAQUS 6.11 (Valley Street, Providence, RI, USA) finite element package was used for FEM simulation. The 3D-FEM spinal cord model consisted of gray matter, white matter, and pia mater (Figure 1). The spinal cord was assumed to be symmetrical about the midsagittal plane, such that only half the spinal cord required reconstruction and the whole model could be integrated by mirror image. The vertical length of spinal cord for computed tomography (CT)

measurement was two vertebral bodies (about 40 mm). In order to simplify calculation, the denticulate ligament, dura, and nerve root were not included. The pia mater was included since it has been demonstrated that spinal cord with and without this component shows significantly different mechanical behavior.<sup>10</sup>

A rigid, hill-shaped body with a slope of 30° was used to simulate C-OPLL with measuring paper.<sup>6</sup> In addition, to match the posterior upper and lower edge of the vertebral body, the upper and lower edge of the hill-shaped OPLL was set. To assume segmental range of motion (ROM) at the level of maximum cord compression, the center of the hill-shaped OPLL had established discontinuity (Figure 1A). The lamina model was established by CT measurement (Figure 1B).

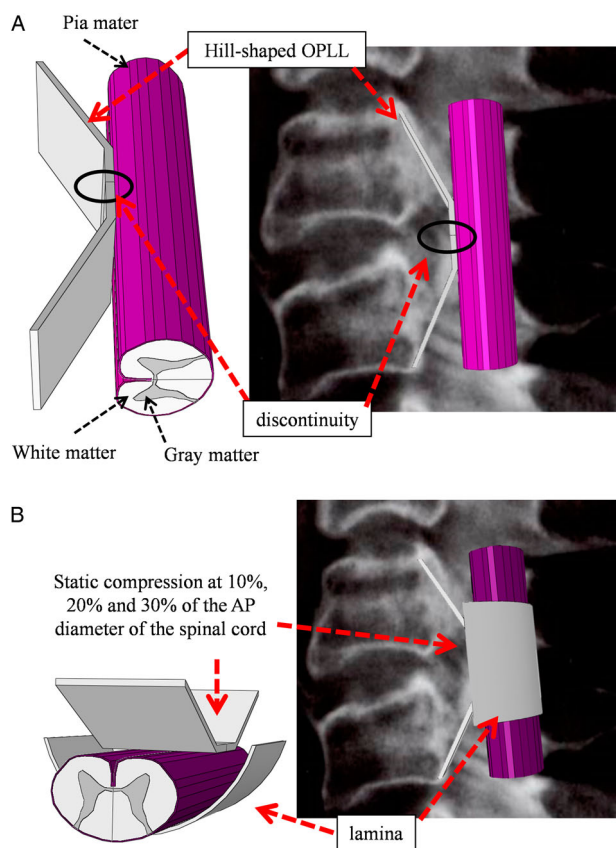
The mechanical properties (Young's modulus and Poisson's ratio) of the gray and white matter were determined using data obtained by the tensile stress strain curve and stress relaxation under various strain rates.<sup>11,12</sup> The mechanical properties of pia mater were obtained from the literature.<sup>12</sup> The mechanical properties of hill-shaped ossification and lamina were stiff enough for the spinal cord to be pressed. Based on the assumption that no slippage occurs at the interfaces of white matter, gray matter, and pia mater, these interfaces were glued together. Since there are no data on the friction coefficient between the lamina and spinal cord, this was assumed to be frictionless. Similarly, the coefficient of friction between the hill-shaped ossification and spinal cord was assumed to be frictionless at the contact interfaces.

The spinal cord, hill-shaped ossification, and lamina model were symmetrically meshed with 15 or 20-node elements. The total number of elements was 11,438 and the total number of nodes was 67,434.

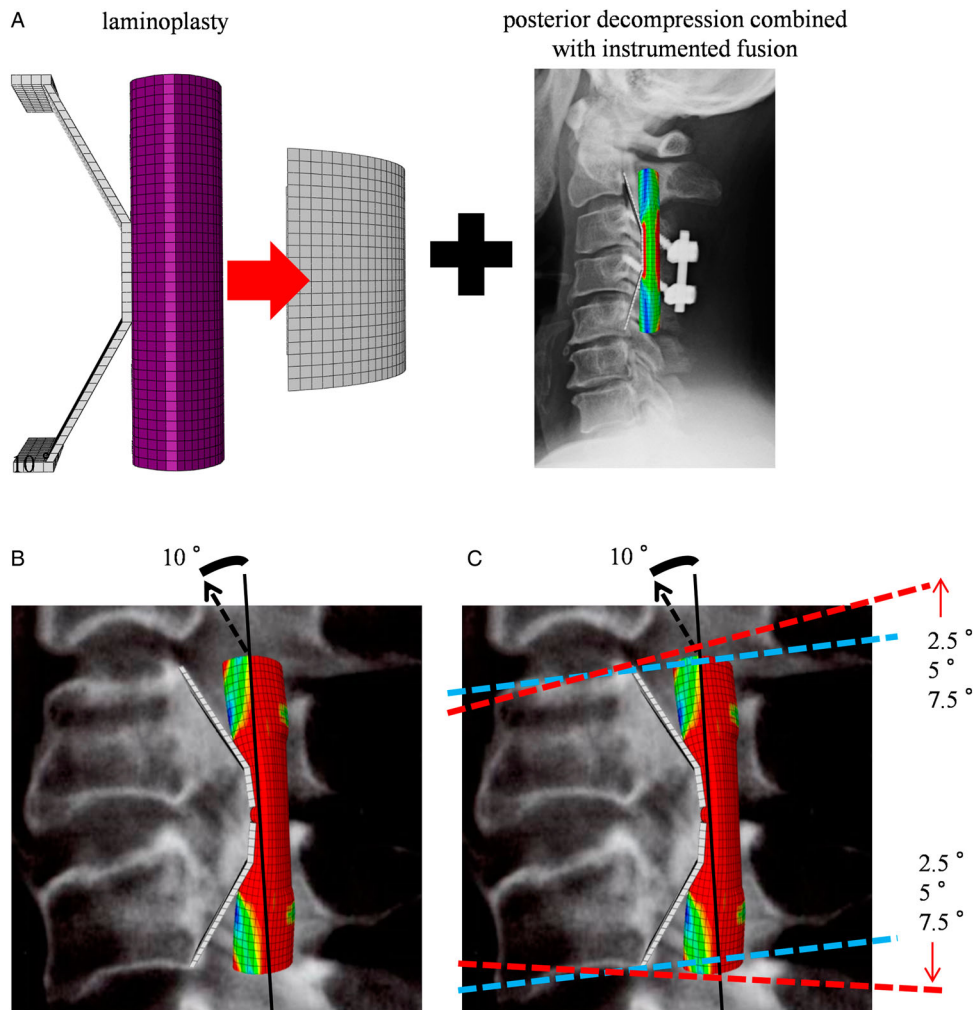
For the preoperative model, compression was simulated by C-OPLL with a hill-shaped ossification. The top and bottom of the spinal cord and the lamina were fixed in all directions, and then 10%, 20%, and 30% anterior compression of the anterior-posterior diameter of the spinal cord was applied to the spinal cord by OPLL (Figure 1B).

The posterior decompression with fusion model was developed by shifting the vertebral arch backwards, while 10%, 20%, or 30% compression was applied to the spinal cord, and the spinal cord was hypothesized not to move after surgery (Figure 2A).

The post-decompression advanced kyphosis model was developed by displacing the spinal cord in kyphosis of 10°, while 10%, 20%, or 30% anterior compression was applied to the spinal cord after the vertebral arch was shifted. Because Henderson reported that stretch injury of the spinal cord is caused when it is displaced



**Figure 1.** (A) The 3D-FEM spinal cord model consisted of gray matter, white matter and pia mater. The center of the hill-shaped OPLL showed an established discontinuity. (B) For the preoperative model, compression was simulated by C-OPLL with a hill-shaped ossification. Anterior compression at 10%, 20% and 30% of the anterior-posterior diameter of the spinal cord was applied to the spinal cord by OPLL.



**Figure 2.** (A) The posterior decompression with fusion model was developed by shifting backwards the vertebral arch. (B) The post-decompression advanced kyphosis model was developed by displacing the spinal cord in kyphosis by 10° after the vertebral arch was shifted. (C) Kyphosis+intervertebral mobility model. The spinal cord was displaced by kyphosis of 10°. To add mobility comparable to that of the vertebral body, each of the upper and lower margins of the OPLL site was then moved in the direction of flexion by 2.5° (total of 5°), 5° (total of 10°) or 7.5° (total of 15°).

in kyphosis and stretched out, the spinal cord was stretched by 20% toward the head and in the direction of kyphosis (Figure 2B).<sup>14</sup>

Furthermore, to develop the post-decompression advanced kyphosis+intervertebral mobility model, while 10%, 20%, or 30% anterior compression was applied to the spinal cord after the vertebral arch was shifted, the spinal cord was displaced in kyphosis of 10°. Then, to add mobility comparable to that of the vertebral body, each of the upper and lower margins of the OPLL site was moved in the direction of flexion by 2.5° (total 5°), 5° (total 10°), and 7.5° (total 15°) (Figure 2C).

In total, 18 different compression combinations were evaluated, and the average von Mises stress was recorded in each cross section.

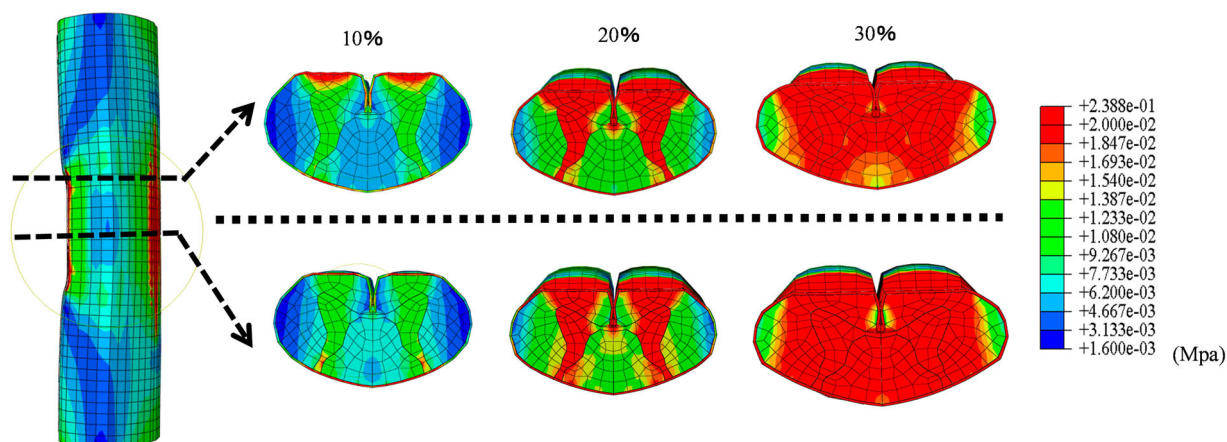
## Results

For the preoperative model, stresses were very low at 10% compression of the AP diameter of the spinal cord. At 20% compression, stress distributions were confined to gray matter and anterior funiculus. At 30% compression, the stresses on gray matter, anterior funiculus, lateral funiculus, and posterior funiculus all increased (Figure 3).

In the posterior decompression with fusion model, stress decreased in comparison to the preoperative compression model. However, when 20% and 30% compression persisted in the spinal cord, stress persisted at the ventral and dorsal sides of the spinal cord (Figure 4A).

In the post-decompression advanced kyphosis model, only a mild increase in stress was observed in the gray

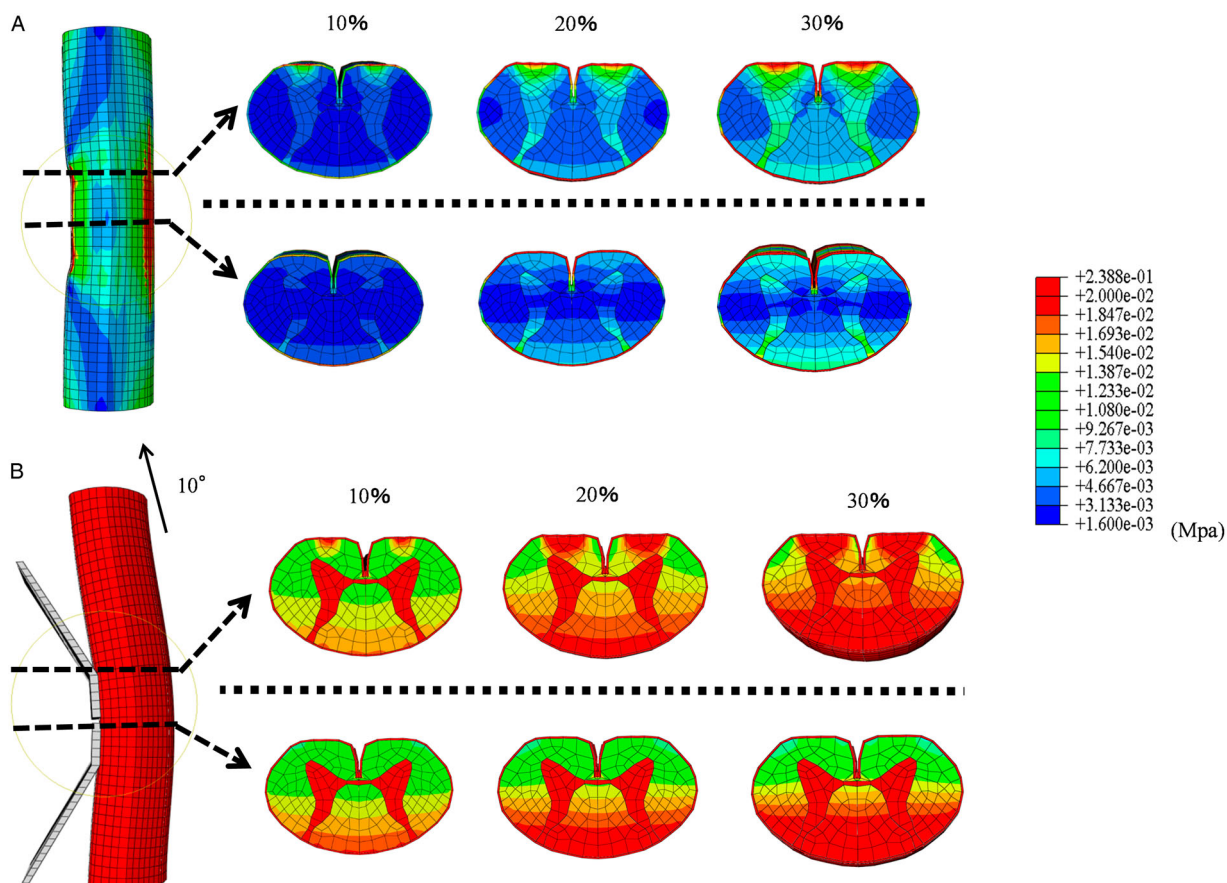




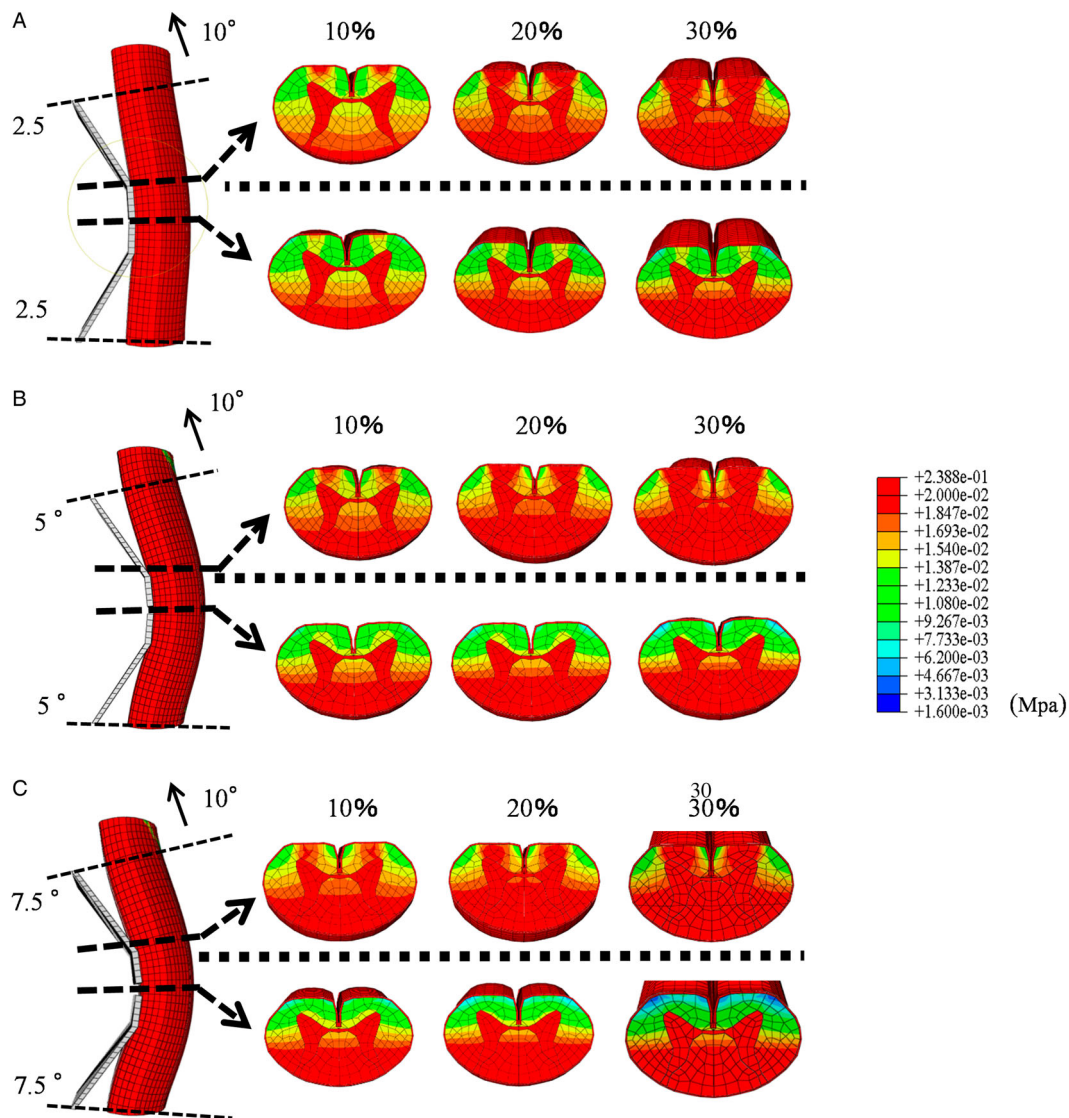
**Figure 3. Preoperative model.** The right color bar is a classification graph according to the stress distribution. As the compression is increased, the stress distribution in the spinal cord is also increased.

matter and the posterior funiculus when 10% compression was applied to the spinal cord. However, stress increased in the anterior and posterior funiculus when 20% compression was applied to the spinal cord. When 30% compression was applied, stress also increased in the lateral funiculus (Figure 4B).

In the post-decompression advanced kyphosis+ intervertebral mobility model (5°), stress increased in the gray matter and the posterior funiculus when 10% compression was applied to the spinal cord, and intraspinal stress increased more than in the advanced kyphosis model when 20% and 30% compression was applied



**Figure 4. (A) Posterior decompression with fusion model.** With posterior decompression, the stress in the spinal cord decreased, but the stress distribution still remained under a compression of 20% and 30%. **(B) Post-decompression advanced kyphosis model.** With advancing kyphosis, the stress distribution in the posterior funiculus and in the gray matter of the spinal cord increased. Intraspinal stress increased according to the degree of residual compression.



**Figure 5.** (A) Post-decompression advanced kyphosis+intervertebral mobility model (5°). (B) Post-decompression advanced kyphosis+intervertebral mobility model (10°). (C) Post-decompression advanced kyphosis+intervertebral mobility model (15°). Intraspinous stress increased more than in the advanced kyphosis model. As intervertebral mobility increased to 10° and 15°, the intraspinal stress increased even with 10% residual compression in the spinal cord. Intraspinous stress increased according to the extent of residual compression and intervertebral mobility.

(Figure 5A). As intervertebral mobility increased to 10° and 15°, intraspinal stress increased even with 10% residual compression in the spinal cord. Intraspinous stress increased according to degrees of residual compression and intervertebral mobility (Figures 5B and 5C).

## Discussion

In general, 3 types of surgical procedures mainly performed for the treatment of C-OPLL are anterior decompression with fusion, laminoplasty, and posterior decompression with fusion. Because compression caused by C-OPLL is located in an ossification lesion in the anterior part, anterior decompression with

fusion, in which complete decompression is attempted, is theoretically the best option.<sup>15,16</sup> However, because it is technically difficult and also causes complications, such as airway edema, displacement of a bone graft, and pain at the site of bone graft harvest, technically easier laminoplasty is selected more often.<sup>2,17</sup> Laminoplasty is a procedure to indirectly decompress the posterior part, but there are also reports that outcomes are poor in some cases of OPLL, with an occupying ratio of 50% or more, and some cases of high intervertebral mobility at the level of maximum cord compression.<sup>2,7</sup> The poor outcomes may be due to failure to relieve residual anterior compression, or because the presence of residual mobility after the

procedure leads to repeated occurrence of injury to the spinal cord or enhanced kyphosis.<sup>2,3</sup> Fujiyoshi et al. defined the line connecting the center of the vertebral canal to cervical vertebrae 2 to 7 as the K-line on a lateral cervical radiograph, and regarded a case of OPLL exceeding the K-line as K-line (–). When posterior decompression is performed in cases of residual compression, K-line (–) cases, residual intervertebral mobility at a high level of cord compression, and advanced kyphosis, addition of posterior fusion is reported to yield favorable outcomes, which are still inferior to those of anterior decompression with fusion.<sup>3</sup>

On the basis of these reports, we analyzed intraspinal stress with a preoperative compression model, a postoperative posterior decompression with fusion model, an advanced kyphosis model, and an advanced kyphosis model with intervertebral mobility at a high level of cord compression. Previous reports on the biomechanics of the spinal cord include a report of analysis performed by Kato *et al.* with hemisected spinal cord models. In their analysis, with clinical relevance in mind, external force was applied to some layer of the spinal cord, but forms of compression, morphology of surrounding tissue, etc. were not taken into consideration.<sup>18,20</sup> Li *et al.* performed analysis with circumferential spinal cord models while the spinal cord itself was moved, but they did not set surrounding compression or other models.<sup>21,22</sup> Takahashi *et al.*, who developed 2-dimensional sagittal plane models of spinal compression, analyzed changes in stress before and after surgery, but did not assess 3-dimensional effects of decompression.<sup>23</sup> Although intraspinal stress caused by behavior or compression of the spinal cord was examined by Cxyz *et al.*, who developed 3-dimensional spinal cord models, and Maikos *et al.* and Greaves *et al.*, who developed models of the vertebral body and spinal cord, they did not mention the clinical effects of decompression, postoperative assessment, etc.<sup>24–27</sup> In another study, we had developed a compression model and a posterior decompression model of C-OPLL and performed analysis to demonstrate that intraspinal stress increases with the progression of kyphosis. However, in this study, only the kyphotic angle was made worse. The same degree of compression was applied, but the instability of anterior components was not assessed.<sup>28</sup> Although postoperative analysis of thoracic OPLL was also performed, this analysis targeted behaviors of the spinal cord, without mentioning mobility of anterior compression.<sup>29</sup> With the analysis models developed in the present study, mobility of anterior components was assessed. As a result, models matched to the clinical features were developed in terms of the pathology

of OPLL and postoperative outcomes, and the conventional analysis was further improved.

Our study was limited to the investigation of stress distribution caused by compression. Other causal factors that can contribute to C-OPLL include ischemia. With respect to blood flow, Ono et al. reported ischemic changes in the white matter and gray matter at the stenosis level.<sup>30</sup> In addition, the effect of the speed of compression of components and the impact of aging were not considered.<sup>31</sup> Discontinuity was set in the middle of OPLL. Deformity of the spinal cord by long-term compression of C-OPLL and apoptotic factors were not considered in the FEM analysis. Moreover, the FEM model used here was simplified in order to facilitate the calculations. Analysis errors were reduced by using a FEM mesh, by assuming the spinal cord was symmetric, and by not including the vertebral body, the denticulate ligament, cerebrospinal fluid, dura, and nerve root. Furthermore, because there are no data on distance between the spinal cord, OPLL lesions, and the vertebral arch, it remains unknown how much the occupying ratio and compression degree are associated. In order for future models to address these various factors, it will be necessary to design models according to specific cases or conditions. We have now emphasized the simplicity of the analysis model, without blood and other components, however, so that it may fully reflect the clinical features of cervical myelopathy for C-OPLL patients.

In the present study, analyses revealed that intraspinal stress is increased by compression due to C-OPLL with hill-shaped ossification, and decreased by posterior decompression with fusion. Although the usefulness of posterior decompression with fusion was demonstrated, intraspinal stress more frequently persisted with higher residual compression. It was assumed that if compression were higher, stress would be more likely to persist. Both the usefulness and limitations of posterior decompression with fusion were suggested. Moreover, intraspinal stress increased again in cases of advanced kyphosis after only posterior decompression was performed, and in cases of OPLL with discontinuous lesions and intervertebral mobility at a high level of cord compression.

With regards to the clinical implications of this study, the following points should be confirmed prior to operation of cervical OPLL patients: (1) the preoperative occupying ratio and the K-line of anterior compression, (2) the intervertebral mobility and discontinuity of ossification as determined by examination with X-rays and CT, and (3) whether there is reinforcement of kyphosis and exacerbation of spinal cord compression by



anteflexion and retroflexion as seen by MRI or CT myelography. These evaluations may help to guide the choice of operation such as the range of fixation, as well as informing about the likely prognosis.<sup>2,3,7</sup>

## Conclusion

We performed stress analyses with a preoperative compression model, a decompression with fusion model, and a combined model of postoperative residual compression and residual instability in C-OPLL with hill-shaped ossification.

Although instrumented fusion after posterior decompression is useful, stress to the spinal cord tended to persist in cases of high residual compression. Moreover, it was found that when fusing is not performed and results in instability, intraspinal stress increases again. Thus, in cases of high residual compression and instability after posterior decompression, anterior decompression with fusion or posterior decompression with instrumented fusion should be considered as previously reported.

**Author declaration** No benefits in any form have been received or will be received by a commercial party related directly or indirectly to the subject of this article.

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